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WATERTOWN ARSENAL

LABORATORY

REPORT

NO. WAL 710/1044
O. O. Project Number: TB4-10H
D/A Project Number: 593-08-020

BALLISTIC EVALUATION OF VARIOUS PERSONNEL ARMOR MATERIALS

BY

R. A. Muldoon
Physicist

DATE 9 March 1954

WATERTOWN ARSENAL
WATERTOWN, MASS.

TITLE

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Authorized by:	ORDTB-Materials	9 March 1954
D/A Project Number:	593-08-020	
O.O. Project Number:	TB4-10H	
Report Number:	WAL 710/1044	
Priority:	1C	
Title of O.O. Project:	Armor Materials	
Filing Title:	Personnel Armor	

TITLE

Ballistic Evaluation of Various Personnel Armor Materials

OBJECT

1. To develop penetration equations from available ballistic data for Doron, Type II, bonded nylon, unbonded nylon, 24ST-4 aluminum alloy, 75ST aluminum alloy and Hadfield manganese steel which express the ballistic limit for the fragment-simulating type projectiles as a function of the weight of target material disposed at 0° obliquity.

2. To employ these equations to determine the relative effectiveness of various personnel armor materials for protection against attack by fragment type missiles at 0° obliquity.

SUMMARY

Tests conducted at Aberdeen Proving Ground on personnel armor materials using fragment-simulating type projectiles have yielded the velocity required to perforate a given weight of material per unit protected area at 0° obliquity - for a wide variety of materials over an extensive range of target weights (10 to 70 ounces per square foot). The trends exhibited by these data are such that application of the theory of scale model penetration is suggested. This results in the development of penetration equations of the Poncelet and de Marre form which accurately reproduce the terminal ballistic results over the data range.

The penetration equations for various personnel armor materials are listed as follows:

Material	Equation	Data Range ($\frac{\sigma}{d}$ = oz/ft²/in)
24ST-4 aluminum alloy	$V_L = 435 \exp\left[.0048 \left(\frac{\sigma}{d}\right)\right]$	45 - 325
75ST aluminum alloy	$V_L = 417 \exp\left[.0048 \left(\frac{\sigma}{d}\right)\right]$	40 - 325
Bonded nylon	$V_L = 136 \left(\frac{\sigma}{d}\right)^{0.49}$	30 - 290
Unbonded nylon	$V_L = 213 \left(\frac{\sigma}{d}\right)^{0.41}$	30 - 295
Hadfield manganese steel	$V_L = 17.5 \left(\frac{\sigma}{d}\right)^{0.89}$	40 - 185
Doron, Type II	$V_L = 47 \left(\frac{\sigma}{d}\right)^{0.70}$	35 - 290

σ = surface density of target material (oz/ft²)

d = diameter of fragment simulator (inches)

By means of the equations developed the relative effectiveness of various personnel armor materials in protecting against attack by fragment type missiles at 0° obliquity is assessed.

Performance curves are presented to assist the personnel armor designer in selection of the most effective material to defend against fragments of known weight and travelling at known velocity.

CONCLUSIONS

1. Particular forms of the de Marre and Poncelet type penetration equations are found to reproduce the terminal ballistic results of the various personnel armor materials.

2. Of the personnel armor materials tested the following order of decreasing ballistic efficiency is obtained at 0° obliquity:

From surface densities per caliber of attacking fragment simulator, ($\frac{\sigma}{d}$), of 20 oz/ft²/in. to 170 oz/ft²/in.

a. Unbonded nylon
b. Bonded nylon
c. Doron, Type II
d. Hadfield manganese steel
e. Aluminum alloys (24ST-4 and 75ST)

From $\frac{\sigma}{d}$ = 170 oz/ft^2/in. to $\frac{\sigma}{d}$ = 290 oz/ft^2/in.

a. Doron, Type II
b. Unbonded and bonded nylon
c. Aluminum alloys (24ST-4 and 75ST)

3. Both aluminum alloys (24ST-4 and 75ST) are everywhere equal to each other but decidedly inferior over the entire data range to the other materials tested.

4. Everywhere in the region $\frac{\sigma}{d}$ = 20 oz/ft^2/in. to $\frac{\sigma}{d}$ = 170 oz/ft^2/in. the ballistic difference between two consecutively rated materials is small (aluminum alloys excepted) and as $\frac{\sigma}{d}$ increases this difference decreases until at $\frac{\sigma}{d}$ = 170 oz/ft^2/in. all armor materials afford the same resistance to fragment perforation.

5. Within the region $\frac{\sigma}{d}$ = 170 oz/ft^2/in. to $\frac{\sigma}{d}$ = 290 oz/ft^2/in. Doron, Type II, becomes increasingly superior to all materials while bonded and unbonded nylon are equal in performance.

R. A. Muldoon

R. A. MULDOON
Physicist

APPROVED:

J. F. Sullivan

J. F. SULLIVAN
Director of Laboratory

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INTRODUCTION

During the latter part of World War II and especially since the outbreak of the Korean hostilities, intensive effort has been directed towards the development of a lightweight material of good ballistic quality. This material must be of such construction that it can be incorporated into a garment for the foot soldier and afford protection against attack by fragments from high explosive and other fragment producing ammunition. The need for such a garment is amply demonstrated by the fact that approximately 70% of all battlefield casualties are a result of wounds inflicted by fragments and other lightweight low velocity missiles.

For the evaluation of the ballistic capabilities of various materials suggested as personnel armor components, Watertown Arsenal has designed a projectile which incorporates the essential penetrative features of fragment type missiles. This so-called fragment simulator is fired against the material under investigation and the velocity at impact recorded. From a substantial number of impact velocity measurements over a narrow range of velocities (where perforation is likely to occur) the protection ballistic limit (V50) is calculated. The V50 limit represents the velocity level at which there exists a 50% probability that the projectile will defeat the target. Then under identical test conditions - obliquity, weight of body armor per unit area and projectile caliber - the V50 limit discriminates between the ballistic protection afforded by various materials.

The materials evaluated in this report include 24ST-4 and 75ST aluminum alloys, bonded[1] and unbonded[2] nylon, Doron, Type II[3], and Hadfield manganese steel[4].

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1. Bonded nylon panels procured from Victory Plastics Company, Hudson, Mass. Watertown Arsenal Purchase Order 52-947.

2. Unbonded nylon purchased under U. S. Army Specification 7-25, entitled "Cloth, Nylon, Duck, Lightweight," dated 20 May 1947.

3. Doron, Type II, purchased from Continental Diamond Fibre Company, Newark, Delaware. Watertown Arsenal Purchase Order 52-1310 dated 20 September 1951.

4. Hadfield manganese steel purchased under Ordnance Corps Tentative Specification AXS-1170, revision 1, dated 18 December 1945.

THEORY

Penetration studies in the field of steel armor have yielded several general penetration equations[5]. These equations incorporate to a varying degree the multitudinous variables present in a projectile - plate interaction. For a given target material of known mechanical and metallurgical properties, probably the most influential are the mass, diameter and velocity of the projectile and the obliquity and thickness of the target material. Then for a projectile of known geometry impacting a target at a given obliquity, extensive experimental evidence indicates that the success of the target in defeating the projectile is largely dependent upon the ratio of target thickness, e, to projectile diameter, d, (the $\frac{e}{d}$ ratio) and projectile velocity.

The dependence of penetration on dimensionless parameters permits projectile - plate design studies to be made in scale model in the laboratory. These scale model tests utilize armor plate and projectiles of the same quality as corresponding full scale components. Results obtained from these scale model tests may then be used to predict full scale performance.

The development of equations for personnel armor materials reported herein is a result of expressing the penetration data as a function of caliber plate thickness and projectile velocity - the same variables found pertinent in perforation of steel armor by kinetic energy projectiles. The data are found to be well represented in separate cases by equations of the de Marre and Poncelet type.

Before introducing the penetration forms, it will be fruitful to discuss the usual scale model penetration parameters to determine their applicability in the evaluation of personnel armor materials.

A. Projectile

Five fragment-simulating projectiles (see figure 1) are presently used by the Ordnance Corps in the ballistic evaluation of personnel armor. All simulators are heat treated to a uniform hardness of 29-31 Rockwell "c" which is the representative hardness of fragments recovered from detonated American Shell, HE, 105 MM, M1. The geometric and metallurgical design is such that the essential penetrative features of fragment type missiles are preserved, and also consistently

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5. Armament Research Establishment, Proceedings of the Symposium on the Penetration of Armor, September 28-29, 1948, Part I, "Penetration by Conventional Projectiles."

reproducible exterior and terminal ballistic results are guaranteed[6,7]. These projectiles retain the same shape and vary only in mass and diameter. By definition, then, the projectiles are homologous, and

$$\frac{m_1}{d_1^3} = \frac{m_2}{d_2^3} \qquad (1)$$

where:

$m_{1,2}$ = weight of fragment simulators 1 and 2

$d_{1,2}$ = diameter of fragment simulators 1 and 2

B. Target Thickness

In penetration studies of steel armor the thickness, (e), of the target is usually expressed in diameters, (d), of the attacking projectile, i.e. the $\frac{e}{d}$ ratio. It has been found that this parameter influences the mode and consequently the efficiency of the perforation. Tests with steel armor are usually undertaken to improve the quality of steel and no sensible variation in density occurs. The thickness employed, then, serves as an index to the most critical combat consideration - weight of armor required to protect a given area.

With personnel armor penetration efficiency also depends on caliber thickness of the target, but because materials of widely differing density are studied, it is advisable to assess the relative ballistic capabilities of personnel armor materials in terms of the weight required to protect a given area.

now

$$m = \rho \hat{V}$$
$$m = \rho \times l \times w \times e \qquad (2)$$

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6. Watertown Arsenal Laboratory Report No. WAL 760/503 - "Determination of Coefficient of Drag (K_D) and Development of Velocity Loss Equations for the Fragment-Simulating Type Projectiles Used to Evaluate Personnel Armor Materials," R.A. Muldoon, 27 January 1953.

7. Watertown Arsenal Laboratory Report No. WAL 710/1013 - "Personnel Armor - Ballistic Evaluation of M1 and Experimental EX-51-1 Helmets," F. S. Mascianica, 21 August 1953.

where:

m = weight

ρ = density*

$\hat{V}$ = volume

$l \times w$ = surface dimensions

ℓ = thickness

If attention is confined to a surface area of one square foot, then

$$\sigma = \frac{m}{ft^2} = \rho\ell \quad ** \tag{3}$$

where:

σ = surface density

From equation (3), it can be seen that the surface density, σ, is a linear function of the target thickness, ℓ.

C. Poncelet Theory of Penetration

This theory of penetration assumes that the retarding pressure acting on a projectile during penetration is proportional to the square of the velocity.

Then

$$m\dot{V} = -CV^2 \tag{4}$$

where:

m = mass of the projectile

$\dot{V} = \frac{dV}{dt} = V\frac{dV}{dx}$ = instantaneous deceleration of the projectile while perforating the target

x = distance along the target thickness

and C is proportional to the frontal area of the projectile in contact with the target.

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*See Table III for a list of the volumetric densities of the various personnel armor materials.

**Care must be taken that a consistent set of units is employed.

Then

$$C = kd^2 \tag{5}$$

Substituting into equation (4) yields

$$\frac{dV}{V} = -\frac{kd^2}{m} \; dx \tag{6}$$

Now, for homologous projectiles $\frac{m}{d^3}$ is constant. Equation (6) can be written

$$\frac{dV}{V} = -\frac{b}{d} \; dx$$

Integrating between the limits $V = V_L$ at $x = 0$ and $V = V_o$ at $x = \ell$, yields

$$V_L = V_o \exp \; b \; \left(\frac{\ell}{d}\right) \tag{7}$$

where:

V_L[8] = that velocity which will just perforate the target material - limit velocity

V_o = velocity level required before perforation is established

By means of equation (3) the above relation for the limit velocity may be expressed in terms of the more meaningful surface density, σ. Equation (7) now becomes

$$V_L = V_o \; \exp \left[k \; \left(\frac{\sigma}{d}\right) \right] \tag{8}$$

In the defeat of any target, all of the energy possessed by the projectile is not utilized in achieving perforation; but, rather, some of the projectile's energy is dissipated in the form of elastic deformation over the area of impact and in forward displacement of the target. V_o probably represents the dissipation of projectile velocity before the perforative mechanism is established.

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8. The ballistic limits obtained from the equations are not as precise as the V50 protection ballistic limit data. Because of this the symbol V50 is abandoned in favor of V_L. A reason for this deviation is suggested later.

D. de Marre Theory of Penetration:

This theory of penetration asserts on the basis of dimensional arguments that the energy required for perforation is a function of the target thickness and the diameter of the impacting projectile.

$$\frac{mV^2}{2} = A\ d^m e^{3-m} \qquad (9)$$

and

$$\frac{m}{d^3}\ V_L^2 = B\ \left(\frac{e}{d}\right)^{3-m} \qquad (10)$$

where:

m = projectile mass

d = projectile diameter

V_L = that velocity which will just perforate the target material - limit velocity

e = target thickness

B = constant of proportionality

Now $\frac{m}{d^3}$ is constant for any projectile of fixed geometric design. Therefore, for the homologous fragment-simulating projectile, equation (1) reduces to

$$V_L = C\ \left(\frac{e}{d}\right)^{\frac{3-m}{2}}$$

and substituting equation (3) yields

$$V_L = k\ \left(\frac{e}{d}\right)^n \qquad (11)$$

In the ideal case the constants contained in both penetration equations described above would admit of a physical interpretation. In general, however, the penetration process is too complicated and dependent on too many variables to allow such a simple solution. Yet, the success with which particular forms of the penetration equations reproduce the ballistic results of various personnel armor materials does provide a basis for a better understanding of the physical mechanisms involved in the perforation phenomenon. More important, the equations permit an accurate interpolation of the ballistic performance of personnel armor and may be readily incorporated into a more elaborate analysis of the protection afforded combat personnel when subjected to fragmentation bursts from H.E. ammunition.

SOURCE OF DATA

The data contained in this report were compiled by the Armor Branch, Development and Proof Service, Aberdeen Proving Ground at the request of Watertown Arsenal Laboratory. Ballistic testing was initiated in order to develop specification requirements for personnel armor materials. The program is still in progress and, as of yet, the data obtained have not been published.

Each protection ballistic limit, V50, listed (see Table II) for the various target materials is based on at least 100 test rounds fired under carefully controlled laboratory conditions. The zone of mixed results included with each ballistic limit determination represents the maximum range of velocities within which a fragment impact may either perforate or be defeated by the target. From these data the velocity level at which there exists a 50% probability that the projectile will perforate the target - the protection ballistic limit, V50 - is calculated. In view of the large number of tests conducted, it has been estimated that the protection ballistic limit,(V50), deduced from these penetration tests is accurate to within $\pm$ 10 feet per second.

CALCULATIONS

The velocity required for defeat of the target - protection ballistic limit (V50) - is plotted in all cases against surface density per diameter of attacking fragment (analogous to caliber thickness).

If, for 24ST-4 and 75ST aluminum alloy armor, the velocity data are plotted to a logarithmic scale while the corresponding caliber thickness of the target is expressed on a unit scale, a linear trend becomes evident (Figures 4, 5). However, for the other materials, the data manifests linearity when both parameters are plotted on logarithmic scales (Figures 6, 7, 8, 9). The variability of the ballistic data with ($\frac{e}{d}$) is such that it precludes the effort demanded by the more mathematically elegant least squares technique; accordingly, the straight line fits to the data were accomplished visually. This method is justified by the fact that the equations developed reproduce the ballistic results to an accuracy consistent with the assumption that the perforation velocity is dependent solely on the $\frac{e}{d}$ ratio.

For aluminum alloy data plotted on a semi log scale, the slope of the straight line is the constant in the exponential term while the factor by which the exponential term is multiplied is equal to the velocity intercept at $\frac{e}{d} = 0$.

For the data plotted on a log-log scale the slope of the straight line is equal to the exponent of the caliber thickness while the factor by which this term is multiplied is equivalent to the velocity required to perforate the target when $\frac{\sigma}{d}$ = 1.

In both cases the constant multiplicative factor is a measure of the dissipation of energy suffered in establishing the mechanism of perforation operative over the data range, while the slope measures the response of the projectile to increasing target thickness. A large value of this parameter indicates that projectile perforation becomes progressively more difficult with increasing target thickness. The equations developed as a result of this analysis are compiled in Table I and plotted in Figures 10, 11, 12, 13, 14, 15 and 16.

By means of equation (3), the surface density for the personnel armor material under investigation is shown in Figure 3 as a function of the thickness for the 24ST-4 and 75ST aluminum alloys, Hadfield manganese steel, and Doron, Type II, and of the number of layers for the nylon materials. The weight of the fragment-simulating projectile type used in the evaluation of personnel armor materials is presented in Figure 2 as a function of the projectile diameter.

Should a knowledge of the ballistic protection afforded by personnel armor against fragments of a weight class different from those now employed be required, then the diameter of the appropriate simulator may be selected from Figure 2. Now, for any ratio of surface density to fragment simulator diameter falling within the scope of the data range for a given material, the equations developed will permit an accurate determination of the ballistic performance.

RESULTS AND DISCUSSION

The equations developed are based on the assumption that the perforation velocity varies solely with the $\frac{\sigma}{d}$ ratio - the perforation velocity remaining constant when $\frac{\sigma}{d}$ is constant. However, extensive testing with steel armor indicates that with different plate thicknesses and projectile calibers corresponding to a constant, $\frac{\sigma}{d}$, ratio, the ballistic limit does not remain constant. This phenomenon is known as the scale effect and is associated with the variation in physical properties of the armor material at different thickness levels. In general, the change in physical properties with increasing thickness promotes the conditions for a plugging type penetration. The net result is that at constant $\frac{\sigma}{d}$ ratios the larger diameter projectiles will defeat the larger thickness plate at a lower velocity.

This same phenomenon is noticed in tests with personnel armor materials. The magnitude of the velocity variation as a function of projectile caliber or armor thickness is not apparent; but it seems that, like steel, an increase in target thickness and projectile caliber (at a constant $\frac{\sigma}{d}$ ratio) degrades the performance of the target. The influence of the scale effect is small, however, and is neglected in the development of the equations. As a consequence, should subtle differences in the ballistic quality of personnel armor be desired, then recourse should be made to the data. However, in the numerous cases where overall performance against a variety of target thicknesses is required, the equations should prove satisfactory. It appears that the variation between the data and the equations - introduced by neglect of the scale effect - requires that a difference of 100 feet per second in calculated ballistic limits be imposed before a priority in armor quality can be established.

Applying this criterion to the armor materials reported herein reveals that the following order of decreasing ballistic efficiency is obtained at 0° obliquity over the indicated data range.

From $\frac{\sigma}{d}$ = 20 oz/ft^2/in. to $\frac{\sigma}{d}$ = 170 oz/ft^2/in.

a. Unbonded nylon
b. Bonded nylon
c. Doron, Type II
d. Hadfield manganese steel
e. Aluminum alloys, 24ST-4 and 75ST

From $\frac{\sigma}{d}$ = 170 oz/ft^2/in. to $\frac{\sigma}{d}$ = 290 oz/ft^2/in.

a. Doron, Type II
b. Unbonded and bonded nylon
c. Aluminum alloys, 24ST-4 and 75ST

Both aluminum alloys (24ST-4 and 75ST) are everywhere equal to each other but decidedly inferior to the other materials tested over the entire data range.

Everywhere in the region $\frac{\sigma}{d}$ = 20 oz/ft^2/in. to $\frac{\sigma}{d}$ = 170 oz/ft^2/in. the ballistic difference between two consecutively rated materials is small (aluminum alloys in relation to the other materials excepted) and as $\frac{\sigma}{d}$ increases this difference decreases until at $\frac{\sigma}{d}$ = 170 oz/ft^2/in. all armor materials afford the same resistance to fragment perforation.

Within the region $\frac{\sigma}{d}$ = 170 oz/ft^2/in. to $\frac{\sigma}{d}$ = 290 oz/ft^2/in. Doron, Type II, is increasingly superior to all materials, while bonded and unbonded nylon are equal.

Over the range of $\frac{\sigma}{d}$ = 170 oz/ft^2/in. to $\frac{\sigma}{d}$ = 290 oz/ft^2/in. the penetration data for Hadfield manganese steel is sparse and appears to manifest a trend inconsistent with that observed over the lower data range. Because the penetration results are insufficient to establish with definiteness this new trend, no equation has been determined for this range of targets.

These limited data for Hadfield manganese steel, although at variance with the trend obtained against lower thicknesses, are not altogether too surprising. It is most likely an indication of a change in the mechanism of perforation of the armor plate. On the basis of these few results, it would seem that against projectile - plate combinations where $\frac{e}{d} > 185$ the performance of Hadfield manganese steel as a personnel armor component is markedly inferior. However, more firings are needed over this data range to substantiate this contention.

GENERAL CONSIDERATIONS

The variability in shape of actual shell fragments causes a wide variation in penetrative performance. This renders practically impossible any attempt to express with quantitative precision the terminal ballistic performance of actual fragments. However, comparative testing at Watertown Arsenal Laboratory of bonded fabric (nylon) helmet liners with fragment-simulating projectiles and actual shell fragments, both types of approximately the same weight class, has revealed that penetration by the simulator is in good agreement with average results obtained using actual fragments[9].

The penetration equations developed for simulators permit a fair estimate of the performance that can be expected from various personnel armor materials under attack at 0° obliquity by actual fragments of the same weight class. Should future tactical requirements demand that protection be provided against fragments from a different weight class than is represented by the simulators now in use, then the diameter of an equivalent simulator can be calculated from equation (1) and the maximum fragment velocity which a given weight of known material will successfully resist is readily determined from the corresponding equation.

The relations developed in this report apply only when penetration is effected at 0° obliquity. However, during projectile penetration of personnel armor materials at oblique attack, the missile remains undeformed. This would indicate that perforation data on oblique firings could also be represented by some simple functional relationship which incorporates the angle of attack. This has been found true in the case of penetration of steel armor at obliquities where the shot remains undeformed.

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9. Watertown Arsenal Laboratory Report No. WAL 710/1013- "PERSONNEL ARMOR - Ballistic Evaluation of M1 and Experimental EX-51-1 Helmets," F. S. Mascianica, 21 August 1953

TABLE I

Material	Equation	Data Range ($\frac{\sigma}{d}$ = oz/ft²/in.)
24ST-4 aluminum alloy	$V_L = 435 \exp\left[.0048 \left(\frac{\sigma}{d}\right)\right]$	45 - 325
75 ST aluminum alloy	$V_L = 417 \exp\left[.0048 \left(\frac{\sigma}{d}\right)\right]$	40 - 325
Bonded nylon	$V_L = 136 \left(\frac{\sigma}{d}\right)^{0.49}$	30 - 290
Unbonded nylon	$V_L = 213 \left(\frac{\sigma}{d}\right)^{0.41}$	30 - 295
Hadfield manganese steel	$V_L = 17.5 \left(\frac{\sigma}{d}\right)^{0.89}$	40 - 185
Doron, Type II	$V_L = 47 \left(\frac{\sigma}{d}\right)^{0.70}$	35 - 290

- -

V_L = that velocity which will just perforate the target material - limit velocity

σ = surface density of target material

d = diameter of fragment simulator

TABLE II

PENETRATION DATA AT 0° OBLIQUITY

75ST Aluminum

Fragment Simulator (Caliber)	Thickness (Inches)	Protection Ballistic Limit V50 (F/S)	Zone of Mixed Results (F/S)
0.22	.072	620	60
0.22	.156	940	150
0.22	.250	1500	210
0.22	.3125	2070	270
0.30	.072	555	180
0.30	.156	797	100
0.30	.250	1022	160
0.30	.3125	1280	190
0.45	.072	405	150
0.45	.187	643	110
0.45	.3125	850	130
0.50	.102	430	80
0.50	.187	600	90
0.50	.3125	770	100

24ST-4 Aluminum

Fragment Simulator (Caliber)	Thickness (Inches)	Protection Ballistic Limit V50 (F/S)	Zone of Mixed Results (F/S)
0.22	.072	640	60
0.22	.156	1006	110
0.22	.187	1150	130
0.22	.250	1550	160
0.22	.3125	2165	250
0.30	.070	587	120
0.30	.156	817	70
0.30	.250	1090	100
0.30	.3125	1345	200
0.45	.102	560	80
0.45	.187	678	180
0.45	.3125	900	110
0.50	.102	515	80
0.50	.187	626	50
0.50	.3125	820	60

TABLE II (CONT)

Hadfield Manganese Steel

Fragment Simulator (Caliber)	Thickness (Inches)	Protection Ballistic Limit V50 (F/S)	Zone of Mixed Results (F/S)
0.22	.030	1003	160
0.22	.037	1105	180
0.22	.045	1460	200
0.22	.055	1600	270
0.22	.084	1840	110
0.30	.037	840	240
0.30	.055	1282	230
0.30	.080	1695	110
0.45	.030	528	110
0.45	.045	668	100
0.45	.080	1133	130
0.50	.037	520	170
0.50	.045	601	130
0.50	.080	986	150

Doron, Type II

Fragment Simulator (Caliber)	Surface Density (oz/ft^2)	Protection Ballistic Limit V50 (F/S)	Zone of Mixed Results (F/S)
0.22	16.0	1055	160
0.22	32.0	1535	220
0.22	64.0	2525	220
0.30	16.5	865	200
0.30	32.6	1180	230
0.30	63.4	1920	210
0.45	17.0	673	120
0.45	32.4	858	180
0.45	64.5	1365	150
0.50	25.3	698	170
0.50	42.0	952	220
0.50	53.0	1115	240

TABLE II (CONT)

Bonded Nylon

Fragment Simulator (Caliber)	Thickness (Layers)	Protection Ballistic Limit V50 (F/S)	Zone of Mixed Results (F/S)
0.22	10	1165	120
0.22	20	1600	150
0.22	40	2260	200
0.30	10	1015	120
0.30	20	1302	130
0.30	40	1825	120
0.45	10	830	160
0.45	20	1060	130
0.45	40	1470	100
0.50	10	800	130
0.50	20	1015	110
0.50	40	1350	120

Unbonded Nylon

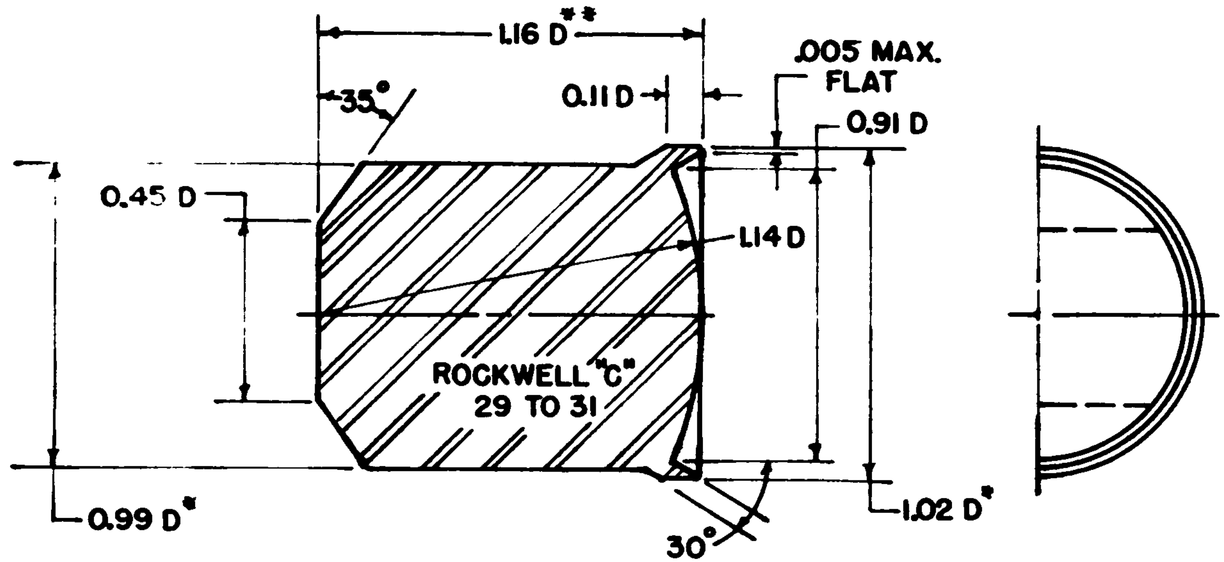
0.22	11	1230	200
0.22	15	1340	240
0.22	22	1650	260
0.22	28	1763	80
0.22	33	1920	150
0.22	39	2070	200
0.22	45	2232	130
0.30	11	1062	120
0.30	22	1420	200
0.30	45	1906	180
0.45	11	950	240
0.45	22	1197	200
0.45	45	1532	140
0.50	11	935	200
0.50	45	1445	140

TABLE III

Volume Densities of Personnel Armor Materials

Material	Volume Density ρ
Aluminum alloy (24ST-4 and 75ST)	230.40 $oz/ft^2/in.$
Hadfield manganese steel	652.03 $oz/ft^2/in.$
Doron, Type II	164.66 $oz/ft^2/in.$
Unbonded nylon	1.44 $oz/ft^2/layer$
Bonded nylon	1.60 $oz/ft^2/layer$

FRAGMENT-SIMULATING PROJECTILE USED IN THE EVALUATION OF PERSONNEL ARMOR



DIAMETER - D (INCHES)	WEIGHT (GRAINS)
.50	207 ± 1.0
.45	147 ± 1.0
.30	44 ± 0.5
.22	17.0 ± 0.5
.15	5.85 ± 0.15

* APPROXIMATE: ACTUAL DIMENSIONS CONTROLLED BY LAND AND GROOVE DIAMETERS OF RIFLE.

** ADJUST LENGTH TO SECURE INDICATED WEIGHT.

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FIGURE 1

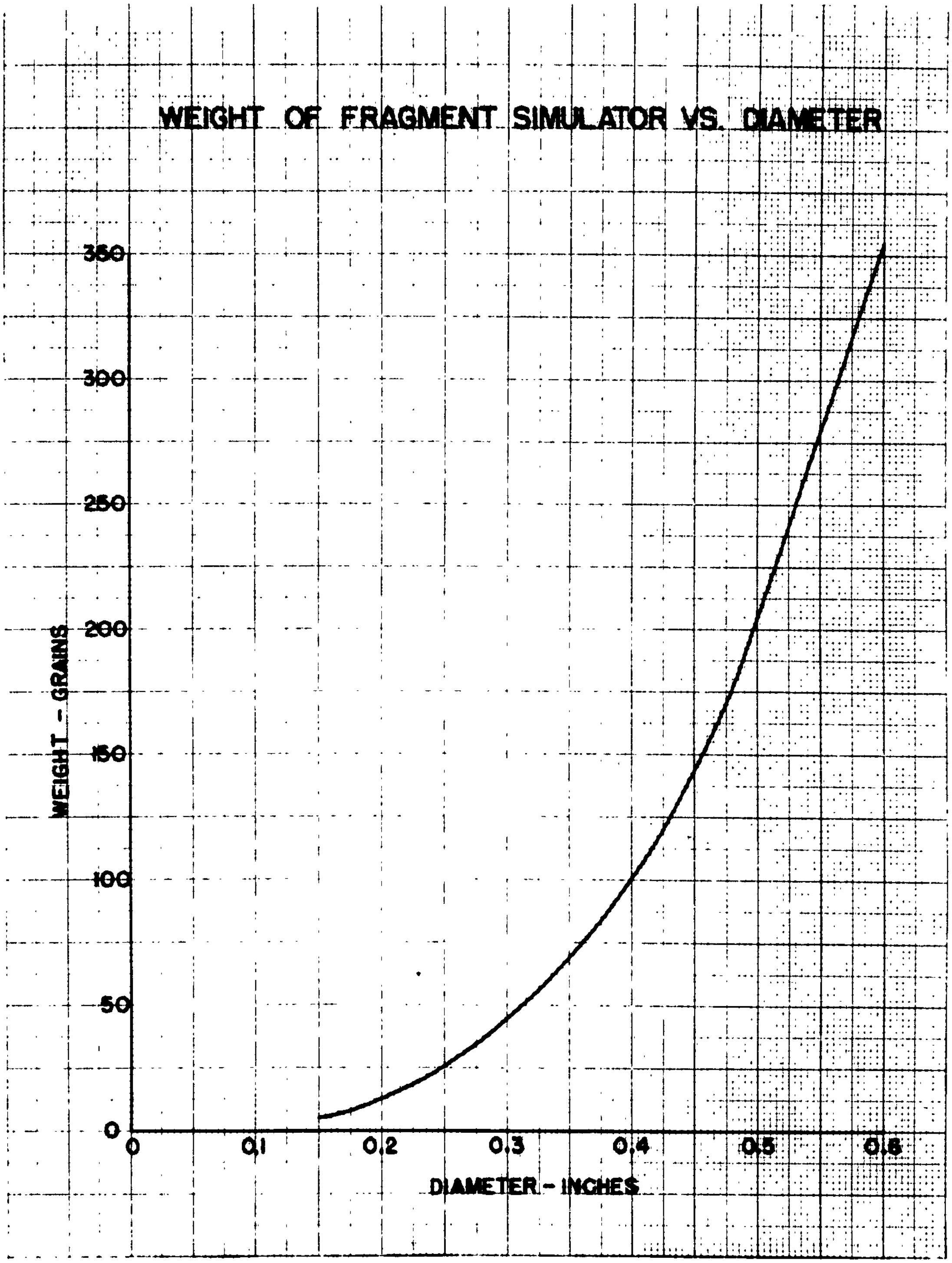

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FIGURE 2

WEIGHT PER UNIT AREA FOR VARIOUS PERSONNEL ARMOR MATERIALS AS A FUNCTION OF THE THICKNESS.

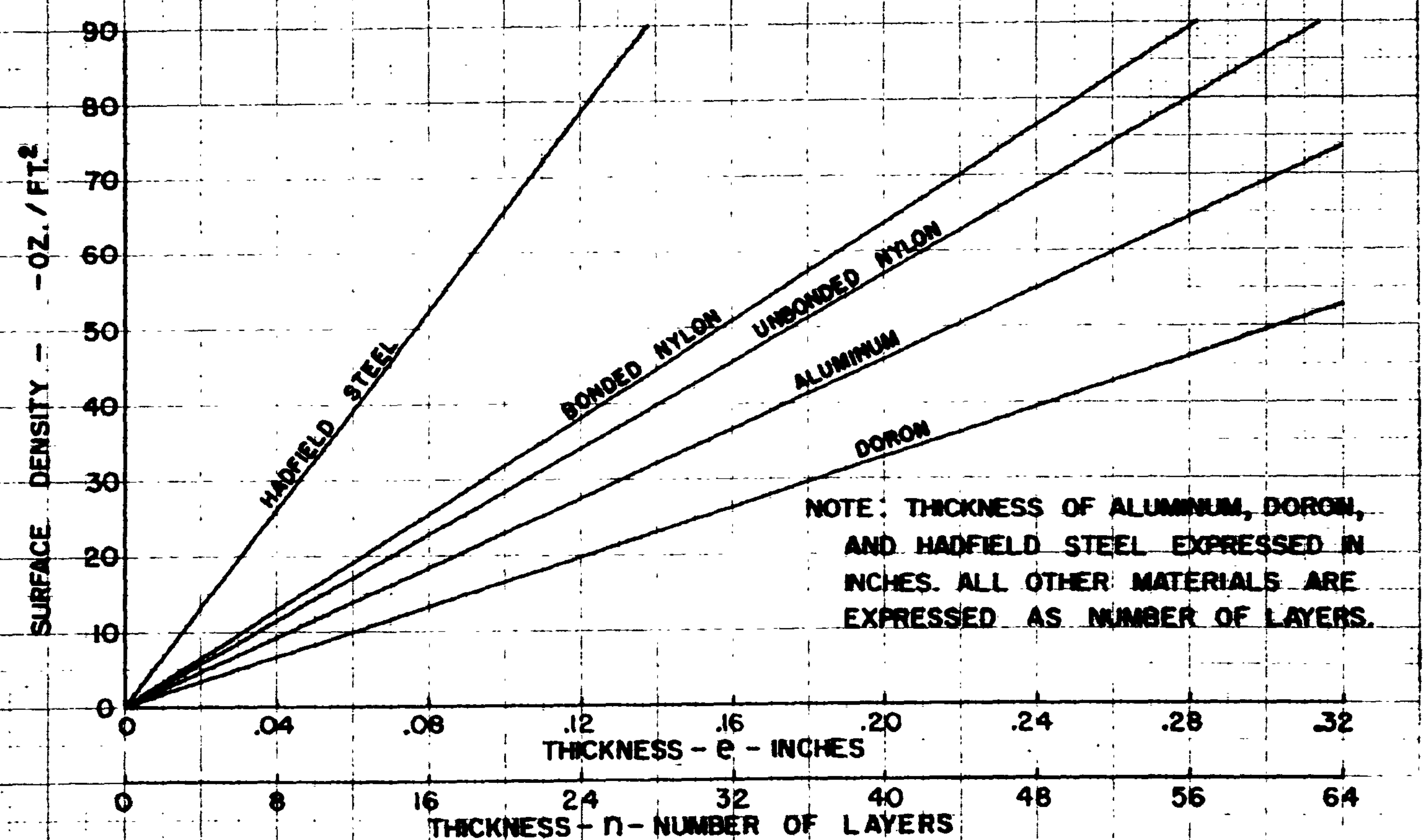

FIGURE 3

W A T E R T O W N   A R S E N A L   L A B O R A T O R Y

WTN.639-12,730

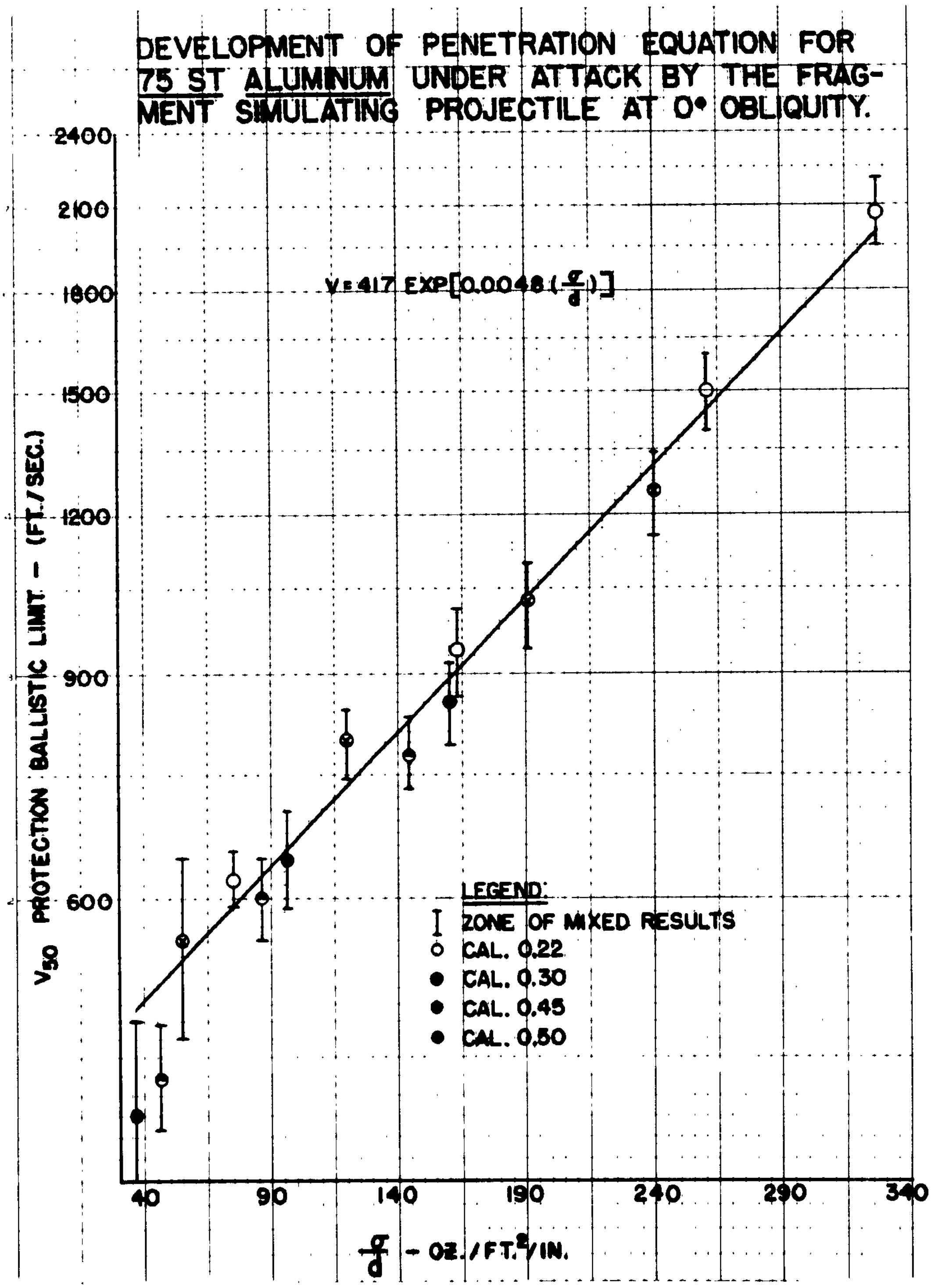

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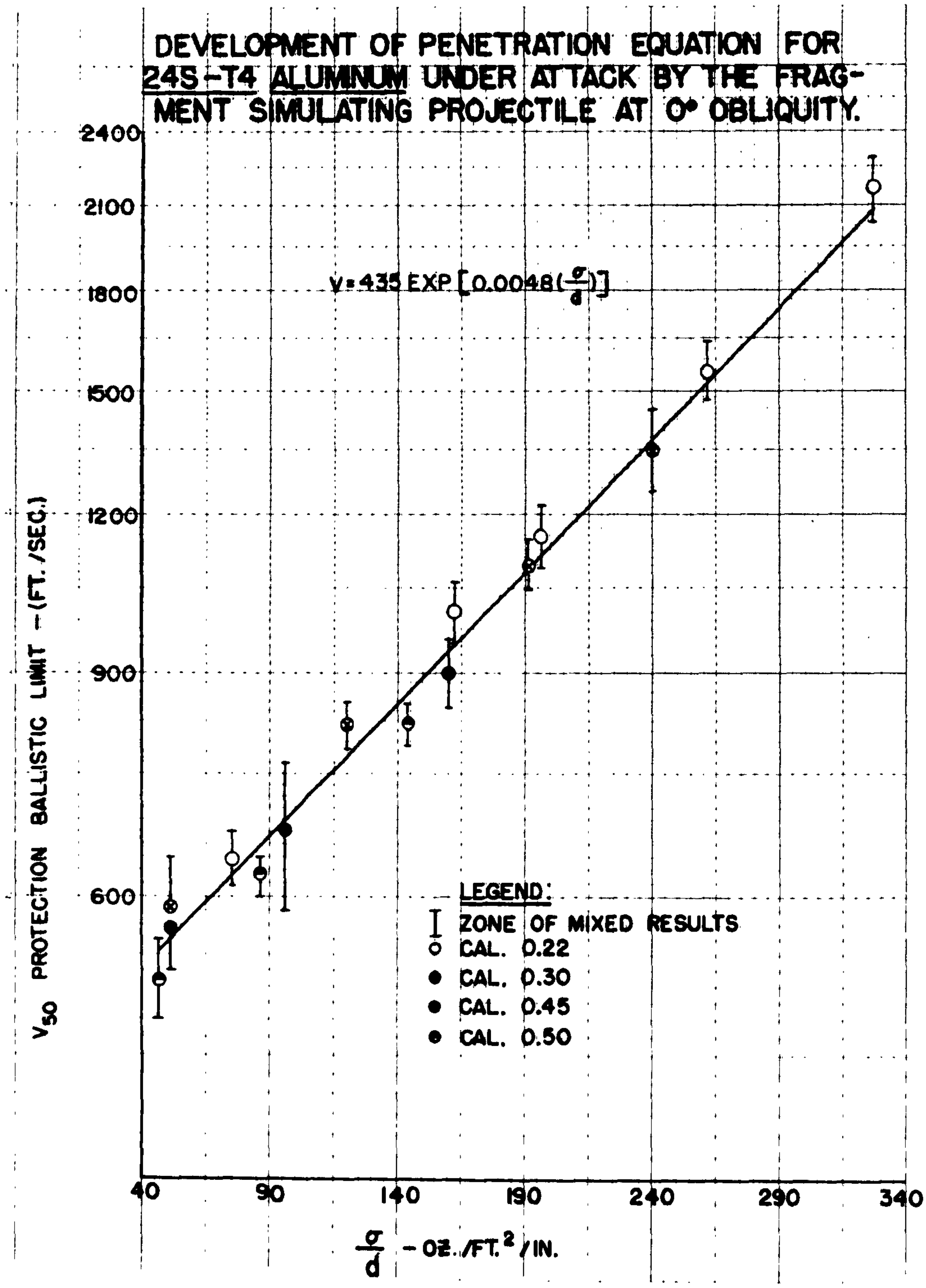
FIGURE 4

WTN.639-12,731


DEVELOPMENT OF PENETRATION EQUATION FOR 24S-T4 ALUMINUM UNDER ATTACK BY THE FRAGMENT SIMULATING PROJECTILE AT 0° OBLIQUITY.
$V = 435 \text{ EXP}\left[0.0048\left(\frac{\sigma}{d}\right)\right]$
2400
2100
1800
1500
1200
900
600
V_{50} PROTECTION BALLISTIC LIMIT —(FT./SEC.)
40
90
140
190
240
290
340
$\frac{\sigma}{d}$ – OZ./FT.^{2}/IN.
LEGEND:
ZONE OF MIXED RESULTS
CAL. 0.22
CAL. 0.30
CAL. 0.45
CAL. 0.50

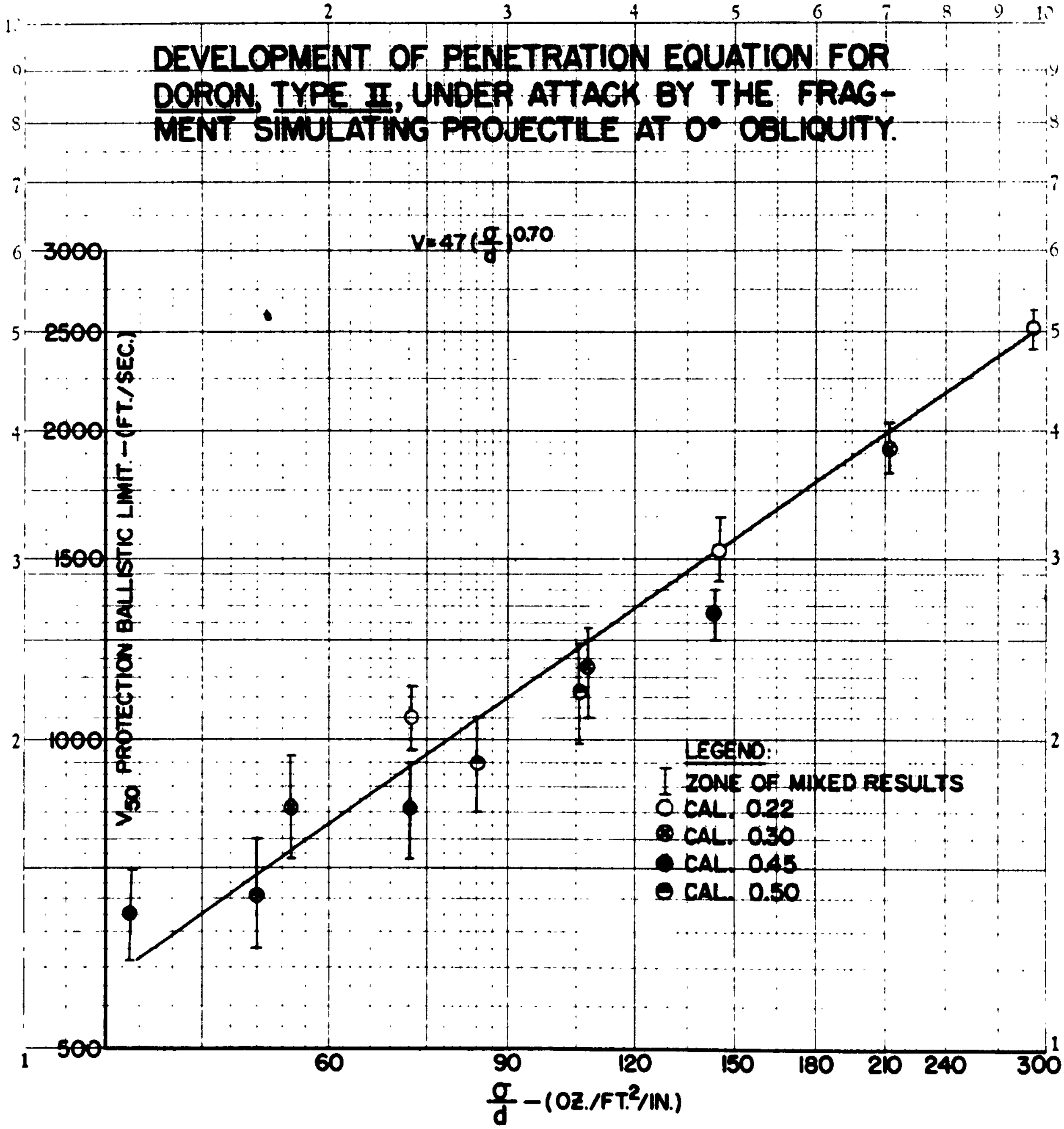


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FIGURE 6

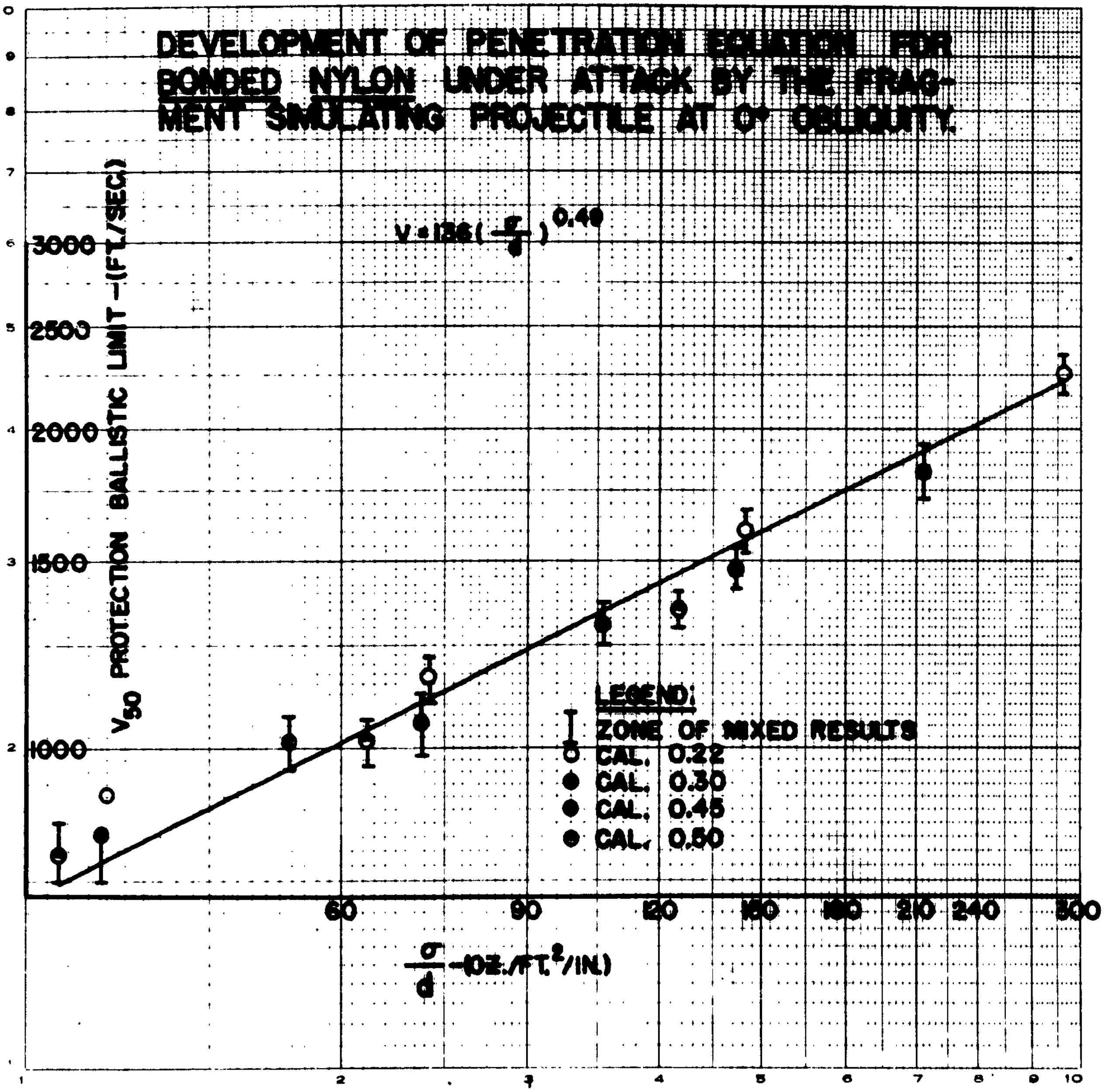

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FIGURE 7

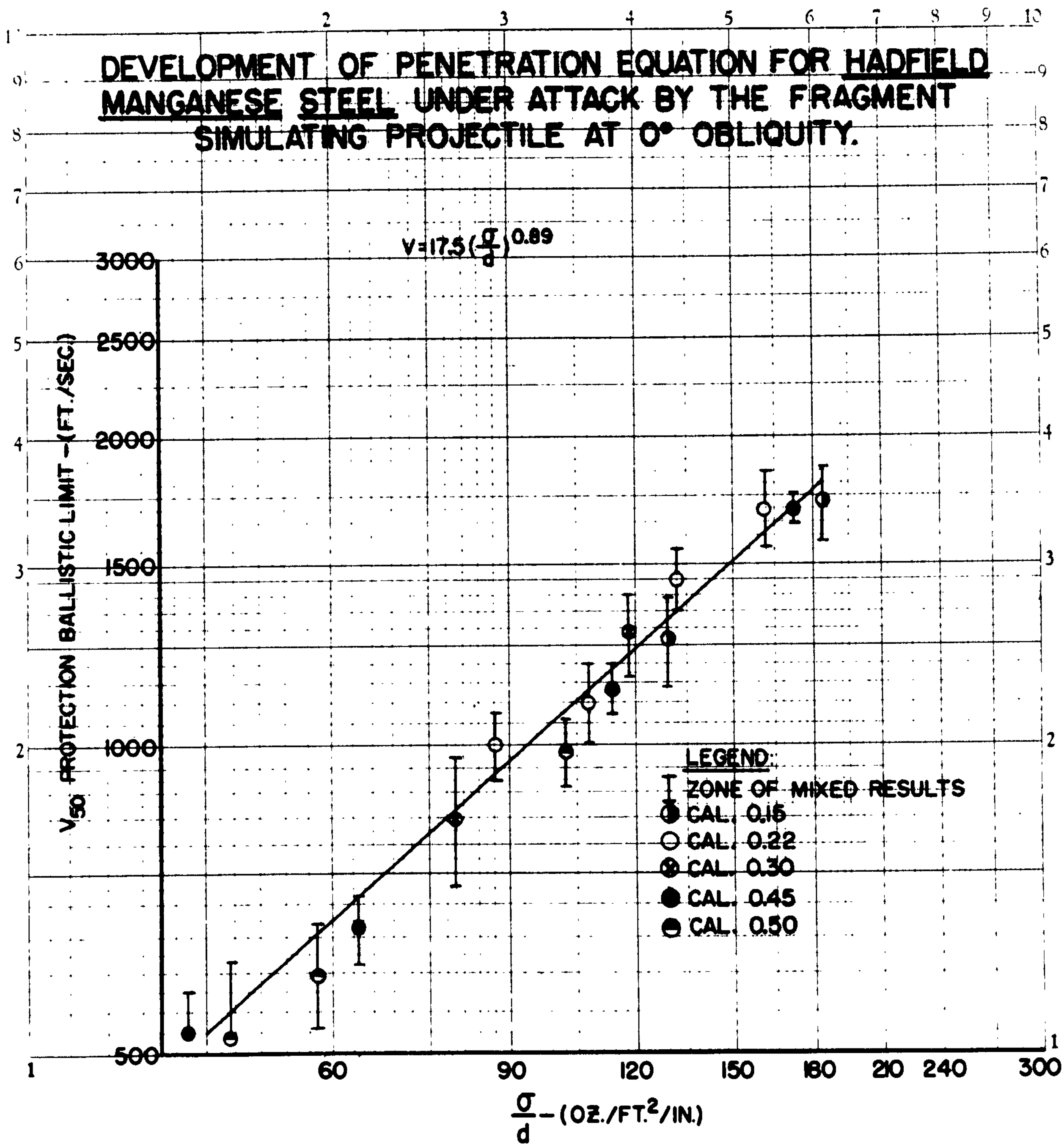

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FIGURE 8

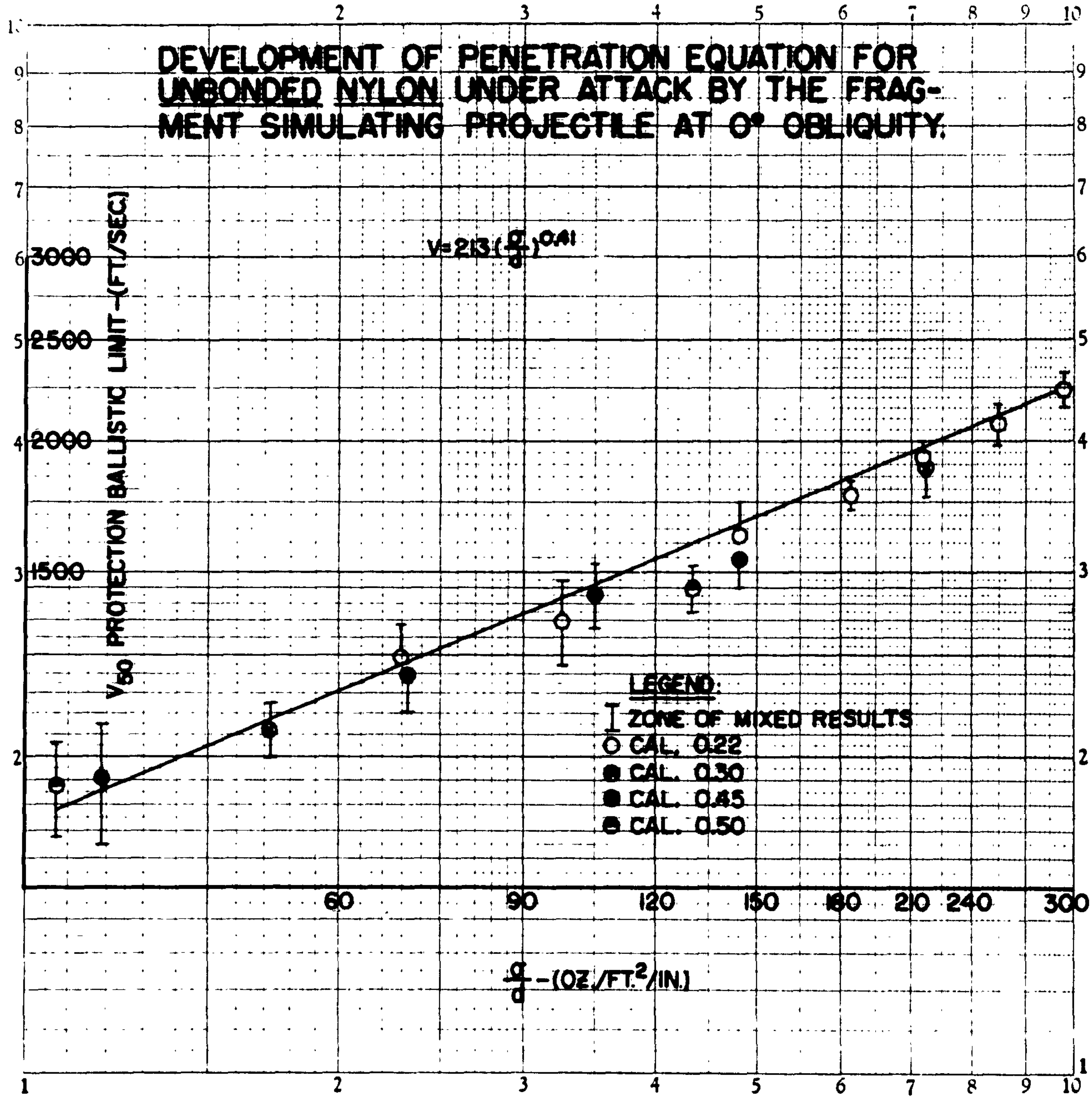

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FIGURE 9

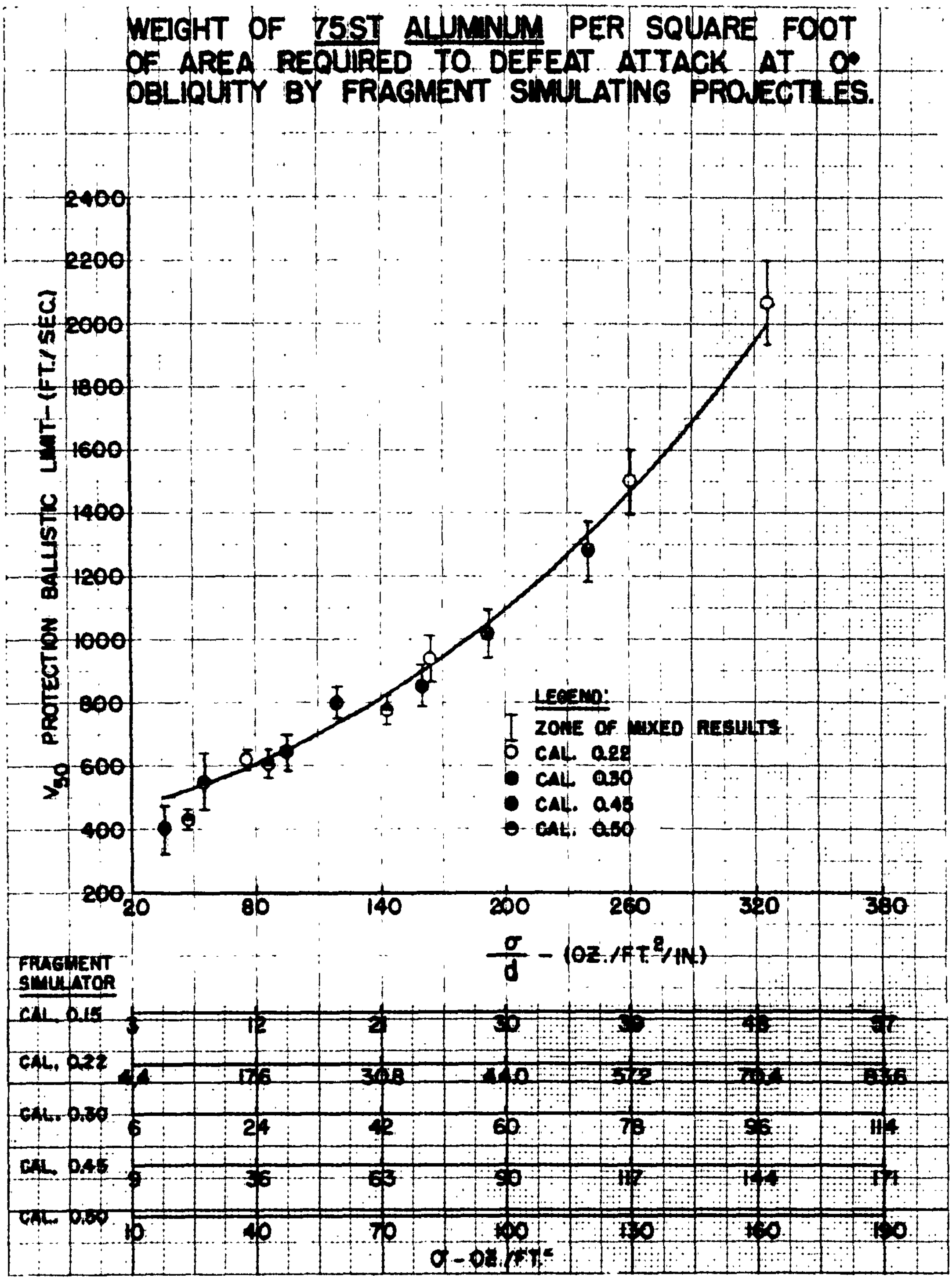

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FIGURE 10

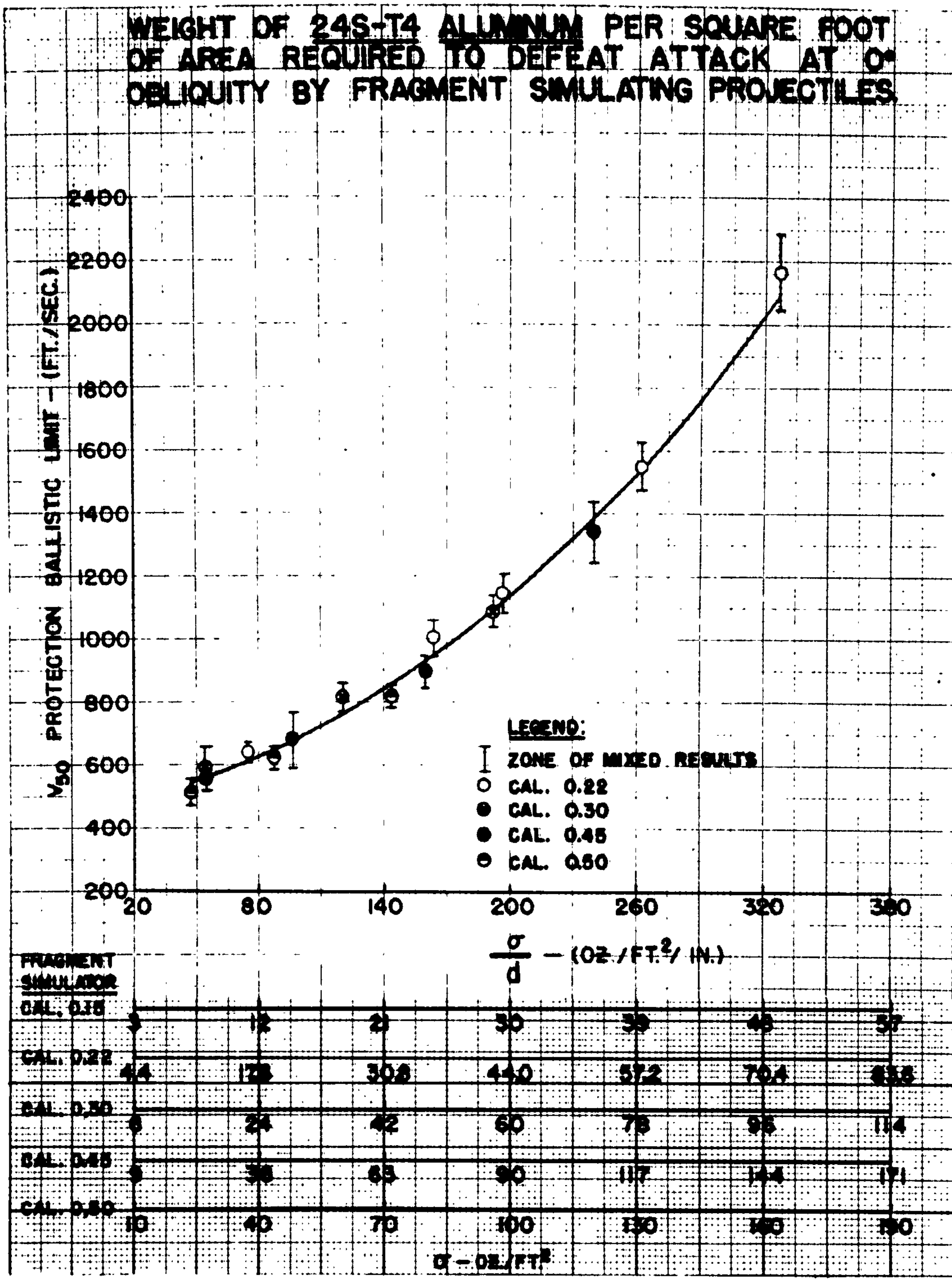

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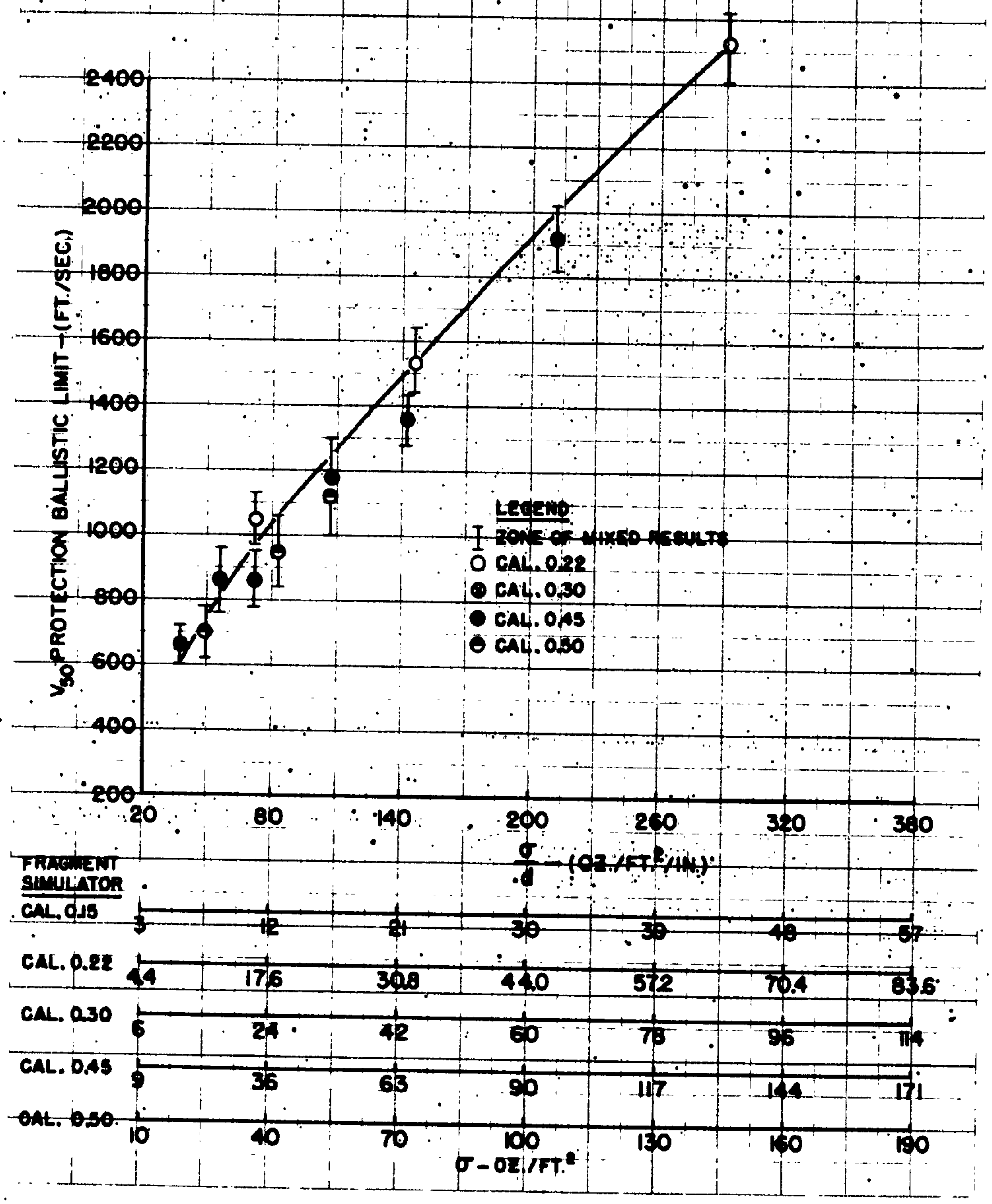
FIGURE 11

WEIGHT OF DORON, TYPE II, PER SQUARE FOOT OF AREA REQUIRED TO DEFEAT ATTACK AT 0° OBLIQUITY BY FRAGMENT SIMULATING PROJECTILES



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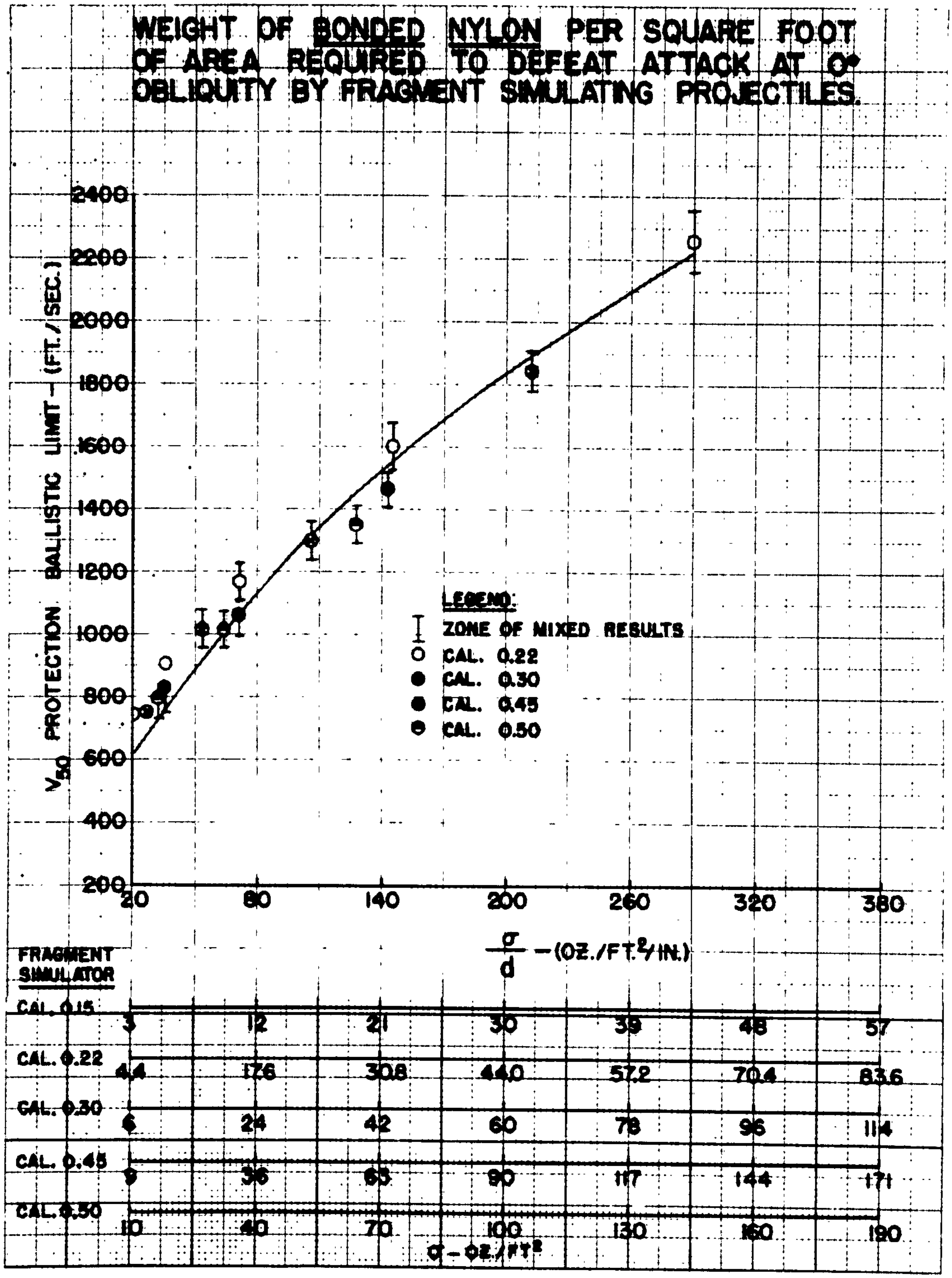

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FIGURE 13

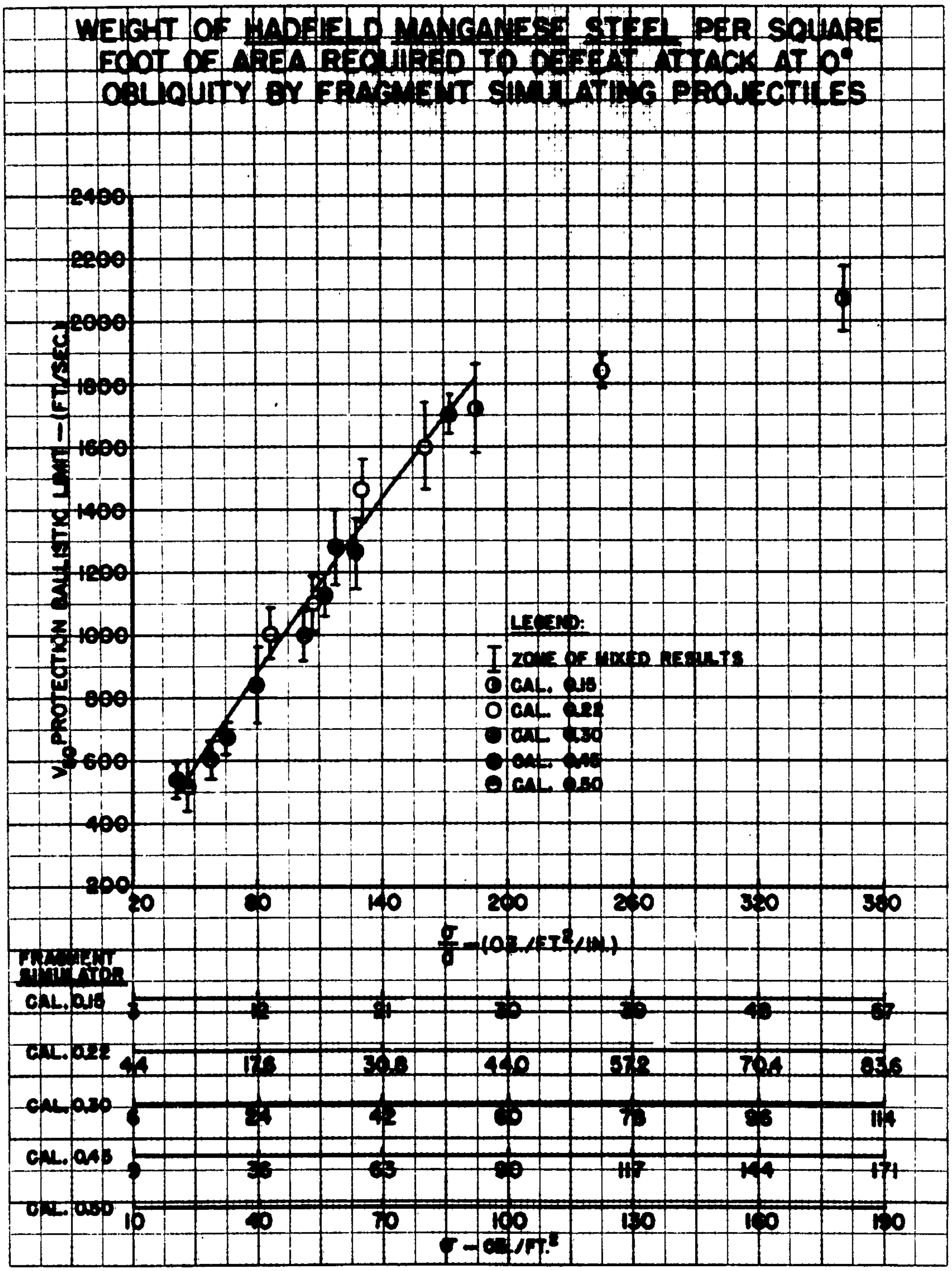

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FIGURE 14

WEIGHT OF UNBONDED NYLON PER SQUARE FOOT OF AREA REQUIRED TO DEFEAT ATTACK AT 0° OBLIQUITY BY FRAGMENT SIMULATING PROJECTILES.

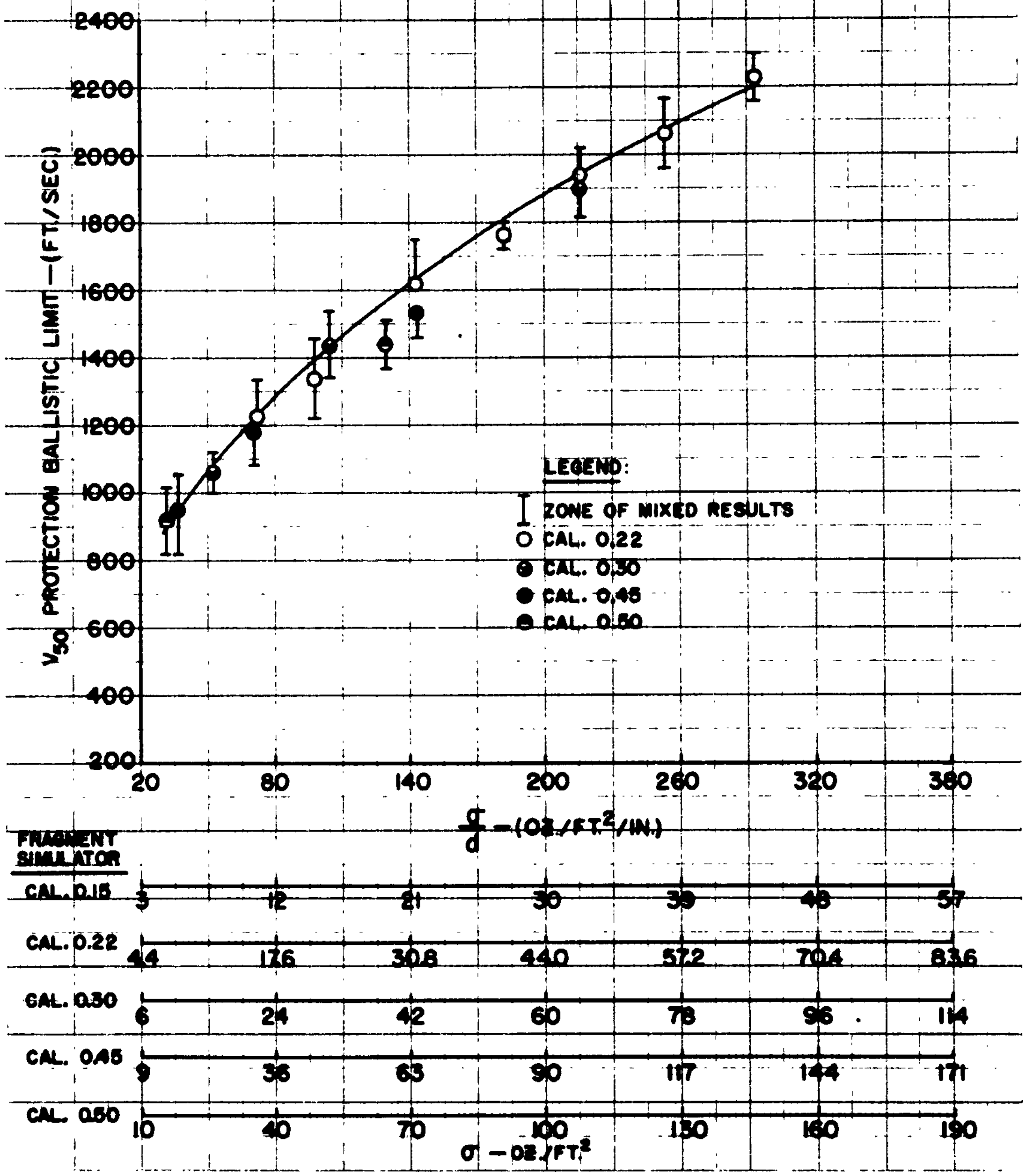

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FIGURE 15

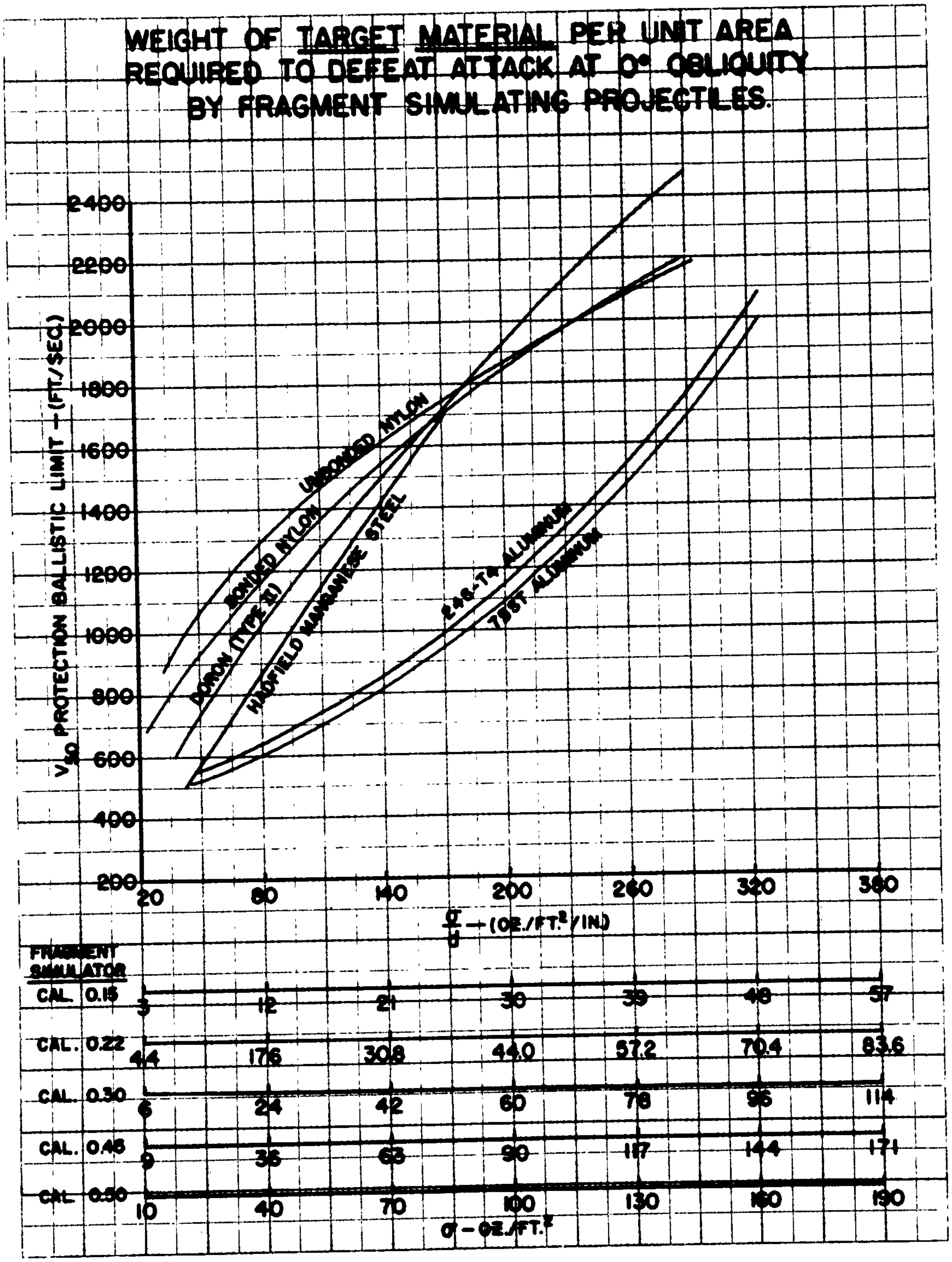

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FIGURE 16

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